

A review of gas engine driven heat pumps (GEHPs) for residential and industrial applications

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Abstract

This study reviews gas engine-driven heat pump (GEHP) systems for residential and industrial applications in terms of energetic and exergetic aspects for the first time to the best of the authors' knowledge. These systems are novel heat pump systems (one of today's promising new technologies). Although the first investigations had been performed at late 1970s, the first merchandized GEHP was produced and introduced in the market in 1985. Gradually, it has become widespread all over the world for various purposes. Main application of GEHPs are for space and water heating/cooling purposes. However, they can be integrated to industrial applications, especially to drying processes.

In this study, historical development of GEHP systems was briefly given first. Next, the operation of these systems was described, while studies conducted on them were reviewed and presented in tabulated forms. GEHPs were then modeled for performance evaluation purposes by using energy and exergy analysis methods. Finally, an illustrative example was given, while the results obtained were discussed. In addition, a new project on integration of GEHP systems to food drying processes in Turkey initiated by the authors was introduced. It is expected that this comprehensive study will be very beneficial to everyone involved or interested in the energetic and exergetic design, simulation, analysis and performance of assessment of GEHP systems.

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Keywords: Gas engine heat pump; Gas engine driven heat pumps; Heat pumps; Exergy; Sustainable development

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1. Introduction

Nowadays, two of main problems in the whole world are depletion of fossil fuels and environmental pollution. The main energy source in the world is fossil fuels and depletion of fossil fuels is a risk for energy poverty in the future. On the other hand, consumption of fossil fuels causes another problem of environmental pollution. Investigations are focused on solving these two problems by two ways: (i) developing alternative energy sources (especially renewable energy sources) and its applications and (ii) improving energy efficiency of equipments that use fossil fuels.

Consumption of energy, especially domestic consumption, mainly occurs in hot water production and space heating, and the source of energy used in these applications are generally supplied from fossil fuels and/or electricity produced from them.

Heat pump (HP) systems are heat-generating devices that transfer heat from low temperature medium to high temperature one and are used in either hot water or space heating applications. HPs generally use vapor-compression cycle or absorption-compression cycle. Although vapor-compression cycles dates back to 1834 and its first commercialized machine was produced at 1850, HPs were not so popular because of their high installation costs [1]. For example, HPs were first commercially produced in the US in 1930s, but after 1970s they have become popular because of their low operating costs. Approximately, one-third of all single-family homes built in the US were heated by HPs in 1984 [2]. Recently, many studies have been progressing in alternative industrial applications of HPs, especially in dehumidification and in drying agricultural products [3–5].

HPs are divided into many categories according to energy sources, namely electric driven HPs (EHPs), chemical HPs, ground source HP, geothermal energy HP, solar assisted HPs and/or hybrid power systems etc. [6–9] and gas engine driven HPs (GEHPs).

Generally, fuel is mainly converted to electrical energy at power plants and the waste heat is discharged to the environment, then electrical energy is transmitted to the HPs and is converted to mechanical energy by motor of the HPs. In this process, energy is converted twice and heat loss is high. However, energy efficiency can become higher if fuel conversion can be located closer to where heat required, heat released in fuel conversion can be efficiently used. Since GEHPs are harmonious with this concept, they are attracted the investigators with the high energy efficiency, especially in heating [10].

A GEHP usually consists of a reversible vapor compression HP with an open compressor driven by a gas fuelled internal combustion engine. Although the efficiency of a gas engine is not very high (about 30–45%), the waste heat of fuel combustion can be recovered by approximately 80%. This is the main advantage of GEHPs [11]. The heat recovery is done by utilizing the energy of exhaust gas and by utilizing the waste heat released by the engine cylinder jacket [11–13].

Since high energy efficiency of GEHPs causes low fossil fuel consumption, the environmental pollution could be reduced. In addition, GEHPs use cheap energy sources, such as natural gas, propane or LPG instead of electricity [11], so GEHPs become an economic choice [10,14,15]. The feature of them is the easy modulation of the compressor speed by adjusting the gas supply. Therefore the optimum working conditions could be effectively obtained [13]. Furthermore, GEHPs can play important social and economic roles by effectively balancing electricity demand, mitigating the electricity peaks and adjusting the energy configuration [14].

In this regard, GEHP systems improve energy efficiency and cause less fossil fuel consumption, so that these systems appropriate to a sustainable development concept. One of the most widely accepted definitions of sustainable development is: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. There are many factors that can help to achieve sustainable development. Today, one of the main factors that must be considered in discussions of sustainable development is energy, and one of the most important issues is the requirement for a supply of energy that is fully sustainable [16,17].

The main objectives of the present study are: (i) to review the studies conducted on GEHP systems by taking into consideration the analysis and utilization areas, (ii) to expose the advantages and disadvantages of GEHP systems, (iii) to anticipate the development of the GEHP systems and (iv) to model GEHPs for performance evaluation purposes by using energy and exergy analysis methods.

2. Description of GEHPs

A GEHP usually consists of a reversible vapor compression HP with an open compressor. It is driven by a gas fuelled internal combustion engine instead of an electric motor. A GEHP system mainly consists of two parts: (i) the HP itself, which includes an open compressor, a

Nomenclature

COP	coefficient of performance (dimensionless)
$\dot{E}$	energy rate (kW)
$\dot{E}_x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
HHV	higher heating value (kJ/kg)
$\dot{I}$	irreversibility rate (kW)
$\dot{IP}$	improvement potential rate (kW)
$\dot{m}$	mass flow rate (kg/s)
PER	primary energy ratio (dimensionless)
RI	relative irreversibility (dimensionless)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (K or °C)
$\dot{W}$	work rate or power (kW)

Greek letters

ψ	flow (specific) exergy (kJ/kg)
η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)

Indices

comp	compressor
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cond	condenser
dest	destroyed (destruction)
eff	effective
evap	evaporator
ex	exergetic
exp	expansion (throttling) valve
in	inlet
mech	mechanical
out	outlet
r	refrigerant
w	water
0	dead (reference) state
.	rate

Abbreviations

DAHX	desorber–absorber heat exchange
EHP	electric driven heat pump
GEHP	gas engine driven heat pump
HP	heat pump
HPGHP	hybrid power gas engine heat pump
HVAC	heating, ventilating and air-conditioning
PID	proportional-integral-derivative
SC	simple absorption cycle
WLHPS	water-loop heat pump system

condenser, an expansion valve and an evaporator, and (ii) the gas engine system [13].

The distinctive part of GEHPs is the gas engine system. Normally their heat efficiency is not very high (about 30–45%). But waste heat can be recovered in GEHPs. Therefore the considerable difference of GEHP systems from conventional EHP systems is its heat recovery and resulted energy efficiency. As an example to the conversion process from fuel to work of conventional EHP systems is shown in Fig. 1, while a comparison between GEHP and conventional EHP systems is illustrated in Fig. 2 [10].

Heat recovery in GEHPs from waste heat of fuel combustion is approximately 80% [11] and this heat is gained by utilizing the energy of exhaust gas and the waste heat released by engine cylinder jacket [11–13]. The utilization could be made generally by two ways: (i) it is transferred directly to air and heated air is used in heating process, and (ii) it is transferred to water and water heating process is done (Fig. 3) [13].

3. A brief historical development of GEHP systems

After realizing the importance of environmental pollution and energy recovery, many investigations have been done. The first investigations on GEHP were performed at late 1970s [18–20]. On 1 April 1977, the first GEHP was started up using in Dortmund–Wellinghofen open air

swimming pool and its performance was evaluated by Bussmann [18]. Fleurschetz [19] proposed a GEHP in an integrated municipal energy supply system and Struck et al. [20] expressed the possibilities and limitations of heating system with GEHP.

At the beginning of 1980s, Heiburg and Lohstaeter [21], Menkveld [22] and Morokoshi et al. [23] conducted field tests about the application of GEHPs for home heating and hot water preparation purposes. In 1981 Japanese government began to support investigations about GEHP. Eustace [24] performed an investigation supported within the framework of the European Commission 2nd Energy R&D Programme in 1984. These showed the affinity of the governments to GEHP.

The first merchandized GEHP produced and introduced in market on April 1985 was named as “gas-multi”. Its first

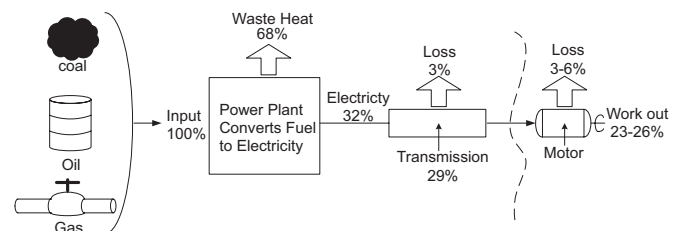


Fig. 1. Losses of conversion process from fuels to work of a heat pump drawn by Lian et al. [10].

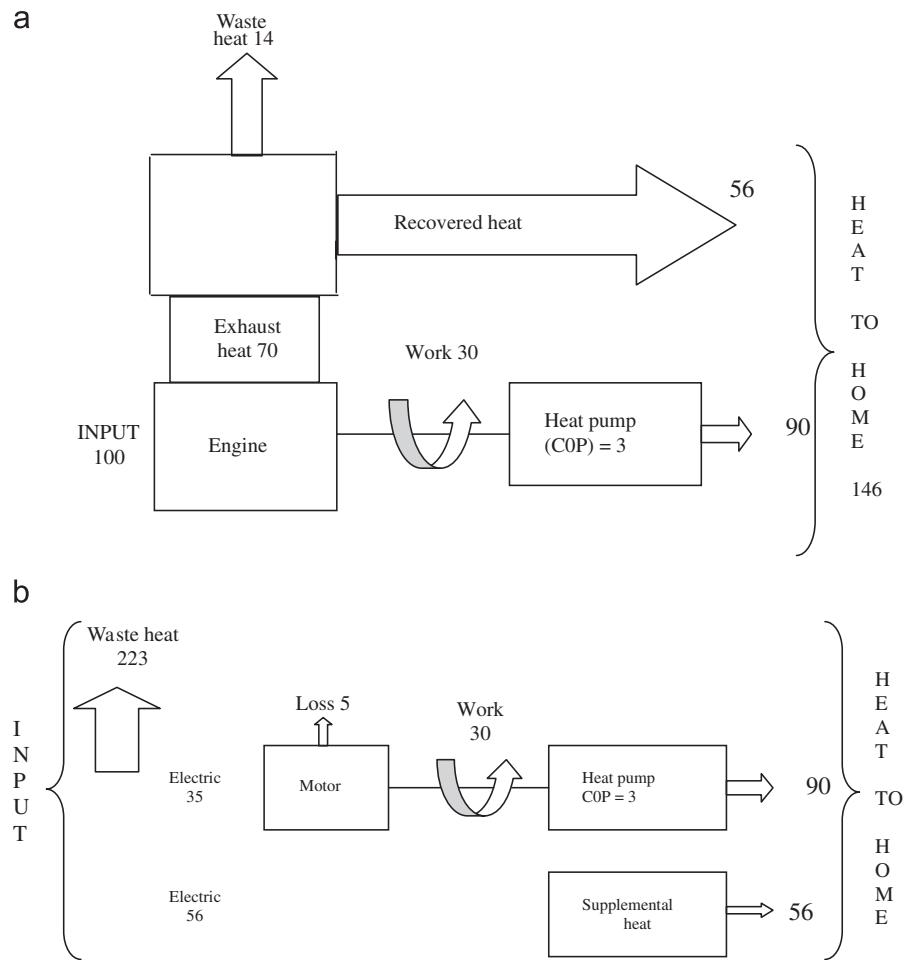


Fig. 2. Comparison of energy conversion process between conventional EHP and GHP [10].

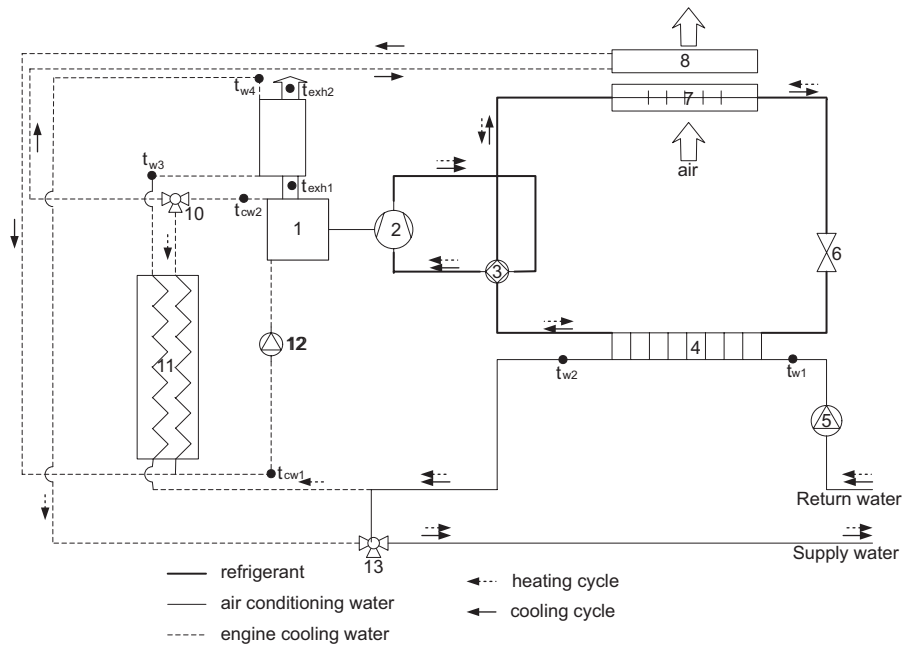


Fig. 3. Schematic diagram of GEHP drawn by Zhang et al. [13]: (1) natural gas engine, (2) open compressor, (3) four-way valve, (4) plate-heat exchanger, (5) supply water pump, (6) expansion valve, (7) finned-tube heat exchanger, (8) heat radiator, (9) gas-to-water heat exchanger, (10) three-way valve, (11) water-to-water heat exchanger, (12) cooling water pump, (13) three way valve.

Table 1
Studies concentrated on GEHP systems' COP values

#	Year	Investigator(s)	Type of study		Type of system		Application		Result(s)
			Theoretical (simulation)	Experimental	Heating	Cooling	Water heating	A/C ^a	
1	1985	Hiroshi et al. [48]	✓		✓	✓	✓	✓	COP _{overall,cooling} = 0.8 COP _{overall,heating} = 1.2 COP _{overall,hot water} = 1.4
2	1995	Wolfe and Getman [29]	✓		✓	✓		✓	COP _{overall,cooling} = .15 COP _{overall,heating} = 1.37
3	2001	Van Dijk and Lemmens [30]	✓		✓			✓	COP _{overall} = 1.1–1.5

^aA/C: air-conditioning.

performance tests were done by Ogura et al. [25]. Since then, many products were introduced in the market by Japanese companies.

Many investigators focused on the system integral energy efficiency and economic aspects of the units by field tests [26–32], improving GEHP by designing and developing its parts [10,33–38], modeling of GEHP systems [13,39–42], its industrial applications [43,44], improving controlling strategies and systems [11,45], and testing its environmental effects [46,47]. Nowadays, investigations on the use of GEHPs have been increased up for residential and industrial application purposes by gaining importance (Table 1).

4. Reviewing the studies conducted on GEHP systems

The primitive GEHPs came to end after gas-multi was developed. After merchandizing GEHP systems, many investigators (Table 2) had devoted their attention on the system integral energy efficiency and economic aspects of the units by way of field tests [26–32]. All field tests showed that GEHP systems were effective in terms of operating costs compared to conventional HP systems. Maddox [26] had performed an analysis for Exeter's new Plaza leisure complex, while Nowakowski et al. [27] conducted it for commercial applications. Wolfe and Getman [29] had made their tests in a Southern climate and measured overall coefficient of performance (COP) as 1.37 for heating and 1.15 for cooling. Van Dijk and Lemmens [30] showed that the max COP of the residential-type diffusion-absorption HP's was 1.5, while average year-round COP was 1.26 and the corresponding gas saving potential was 15% based on the results of 63-unit field tests. Another field test taken into consideration with primary energy ratio (PER) and environmental protection were done by Yang et al. [32]. Their results indicated that GEHP systems were the most advantageous systems. Lazzarin and Noro [14] evaluated the performance of "S. Nicola" HVAC plant in Vicenza set up by a GEHP (Fig. 4) during 3 years of operation. They anticipated the economical advantage whether the plant

was cancelled and replaced with the Vicenza district heating grid service.

Investigations on improving the performance of GEHP systems had also been made. Howe et al. [33] studied on three combined absorption/vapor compression cycles and tested the performances on a theoretical basis. The results indicated that a performance improvement with regard to both capacity and COP could be accomplished with desorber-absorber heat exchange (DAHX) and the simple absorption cycle (SC) cycle up to 31% and 21%, respectively, for heating and 17% and 11%, respectively, for cooling. On the other hand, heat duty increased up to 32% for DAHX cycle and 23% for SC compared with conventional EHP systems. Yagyu et al. [34,35] designed and tested the performance of a gas engine driven Stirling HP (Fig. 5). They estimated the total COP as 1.9 (on a HHV basis) and stated that if the HP system could be pressurized up to 5 MPa, COP would be improved to 2.42 (HHV). Ott et al. [36] outfitted a GEHP with a graphite foam radiator, demonstrated its thermal efficiency and compared it with a conventional radiator. Liu et al. [37] tested the performance of a GEHP with different groups of refrigerants. High COP and PER values were obtained. Lian et al. [10] evaluated the conception of combination of GEHP and water-loop heat pump system (WLHPS) and made an economic analysis (Fig. 6). Ying-Lin et al. [38] designed a hybrid-power gas engine-driven heat pump (HPGHP) system (Figs. 7 and 8). They performed min./max. thermal efficiencies for a power system. The simulation results showed that maximum and minimum thermal efficiencies of a conventional GEHP system were 33% and 22%, respectively, while those of novel HPGHP system were 37% and 27%, respectively.

Another important area was modeling of GEHP systems. The first modeling study about GEHP systems was done by MacArthur and Grald [39]. It was a dynamic model of vapor compression HP, including a detailed mathematical treatment of condenser, evaporator. For the expansion valve and natural gas fueled internal combustion engine lumped-parameter models were developed. Rusk

Table 2
Main studies conducted on GEHP systems

#	Year	Investigator(s)	Type of study		Type of system		Application			Results
			Theoretical (simulation)	Experimental	Heating	Cooling	Water heating	A/C	Other	
1	1989	Howe et al. [33]	✓		✓	✓		✓		DAHX (increase up to) ● Capacity_{cooling} = 31% ● Capacity_{heating} = 17% ● Heat duty = 32% SC (increase up to) ● Capacity_{cooling} = 21% ● Capacity_{heating} = 11% ● Heat duty = 23%
2	1999	Ficarella and Laforgia [15]	✓		✓	✓			✓ (Alcohol distillery)	Fuel consumption = 434.8 kW Heat recovery = 812.03 kW PBP = 3.41 years
3	2000	Yagyu et al. [35]	✓		✓	✓	✓			COP _{overall} = 1.9
4	2003	Zhao et al. [52]	✓			✓	✓			F _{total} = 0.9 → PER = 2.08 F _{total} = 1.5 → PER = 2.43
5	2005	Lian et al. [10]	✓		✓	✓	✓	✓		PBP of GEHP compared to ● CACS → 2 years ● EHP-WLHPS → 2.6 years
6	2005	Li et al. [11]	✓	✓		✓		✓		Cascade fuzzy control system improved
7	2005	Zhang et al. [13]	✓	✓	✓		✓			T _a = 7 °C, S = 1000 RPM → PER = 1.67 T _a = 7 °C, S = 3500 RPM → PER = 1.13 T _a = 9 °C → η _{engine} = 83% → η _{HP} = 5 T _a = 5 °C, Max. power → η _{engine} = 29.7%
8	2006	Xie et al. [52]	✓		✓			✓		PER = 1.76 η = 0.394 ε = 0.291
9	2006	Zhang et al. [51]	✓	✓	✓	✓		✓		GEHP can save ● PER = 23% ● Running cost = 11.3%
10	2006	Lazzarin and Noro [14]	✓		✓	✓		✓		GEHP is appropriate according to economic analysis
11	2007	Li et al. [38]	✓	✓	✓		✓	✓		For conventional GEHP ● max. η_{thermal} = 33% ● min. H_{thermal} = 22% For HPGHP ● max. η_{thermal} = 37% ● min. η_{thermal} = 27%
12	2007	Hepbasli et al. [54]	✓	✓	✓				✓ (Food drying)	Under installation

et al. [40] established a mathematical model consisting of two parts, an engine model and a HP model. This model was more consistent than the others but it had not taken into account any heat recovery being critical for GEHP. According to this model under a constant speed operation, GEHPs were more efficient than EHPs whereas EHPs were

more efficient under variable speed operations. Following this model, Yang et al. [41] improved a dynamic model taking into consideration the exhaust gas. This model included an exhaust gas heat exchanger. Zhang et al. [13] established a steady-state model, which contained an experimental gas engine waste heat model, and also a

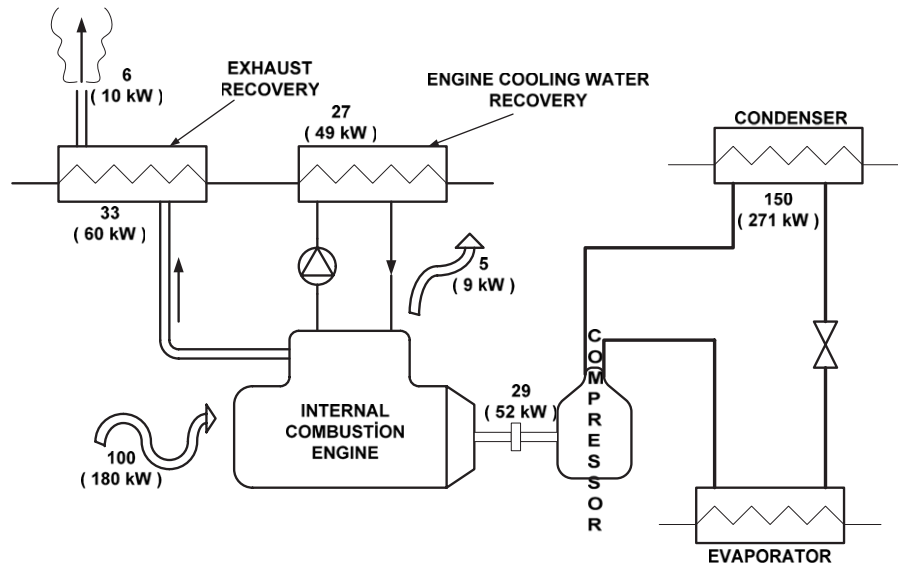


Fig. 4. Schematic figure of the gas engine heat pump installed in the “S. Nicola” HVAC plant (values reported refer to heating mode) [14].

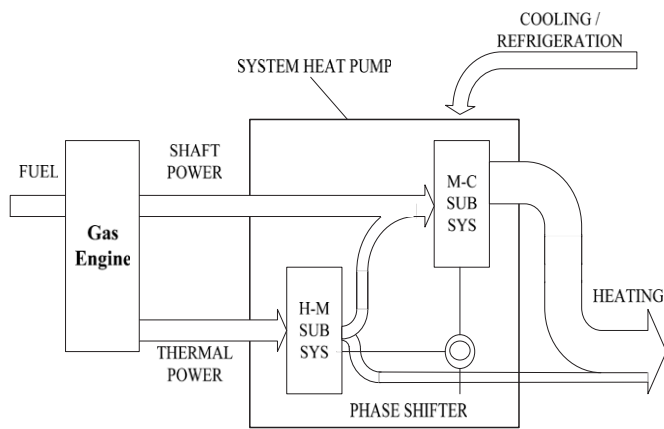


Fig. 5. Schematic of system configuration and heat flow diagram [35].

theoretical heat recovery model. They set up an experimental system as shown in Fig. 9 and also modeled an engine waste heat recovery system, a compressor, heat exchangers, and an expansion valve. It was concluded that although the ambient temperature affected HP performance, it did not affect the gas engine energy efficiency in the constant speed mode so much. However, both HP and gas engine system were remarkably influenced by the engine speed. The GEHP was more energy efficient in the low speed mode. A similar study was conducted to simulate dynamics of a GEHP for design of control algorithm in the cooling mode by Shin et al. [42].

The potential investigation area about GEHP systems is industrial applications of GEHP systems. There are only limited studies on these types of applications in the open literature. Newbert [43] showed that the energy consump-

tion could be reduced by 40% with a coupled GEHP for heating a malt house and for drying of malt, as shown in Fig. 10. Tassou [44] proved that GEHP systems could provide substantial savings in sewage effluent heat recovery applications when compared to natural gas boilers.

The efficiency of GEHP systems could be increased by improving control strategies and systems. Yang et al. [45] developed a new PID-fuzzy controlling method and reported the laws of working conditions of the GEHP perfectly. Then Li et al. [11] improved a cascade fuzzy control structure. A cascade control strategy (Fig. 11) is effective for systems that have large constants and disturbances. It is fit for a system that lacks an accurate model. The result of this study was a stable control system with reduced reaction time and little overshoot in temperature.

The most important feature of GEHP systems is the lower harmful effect to the environment. Creamer and Saunders [46] evaluated an oxidizing catalytic converter for a natural gas engine used in GEHP to increase the CO and hydrocarbon conversion. CO conversion averaged well above 90% whereas hydrocarbon conversion varied between 68.6% and 89.8% over a range of 8 speed and load combinations selected to cover the normal operating range of the engine. Ganji [47] studied on energy efficiencies and source air pollutant emission factors of gas heaters, GEHPs and EHPs for domestic heating. They reported that GEHPs had the highest energy efficiency. Furthermore CO₂ production level of GEHPs' was one half of EHPs.

Many performance tests have also been done to display GEHP system efficiencies (Table 1) [29,30,48]. However they are generally based on COP values of GEHPs. COP values are not an appropriate value for comparing GEHPs

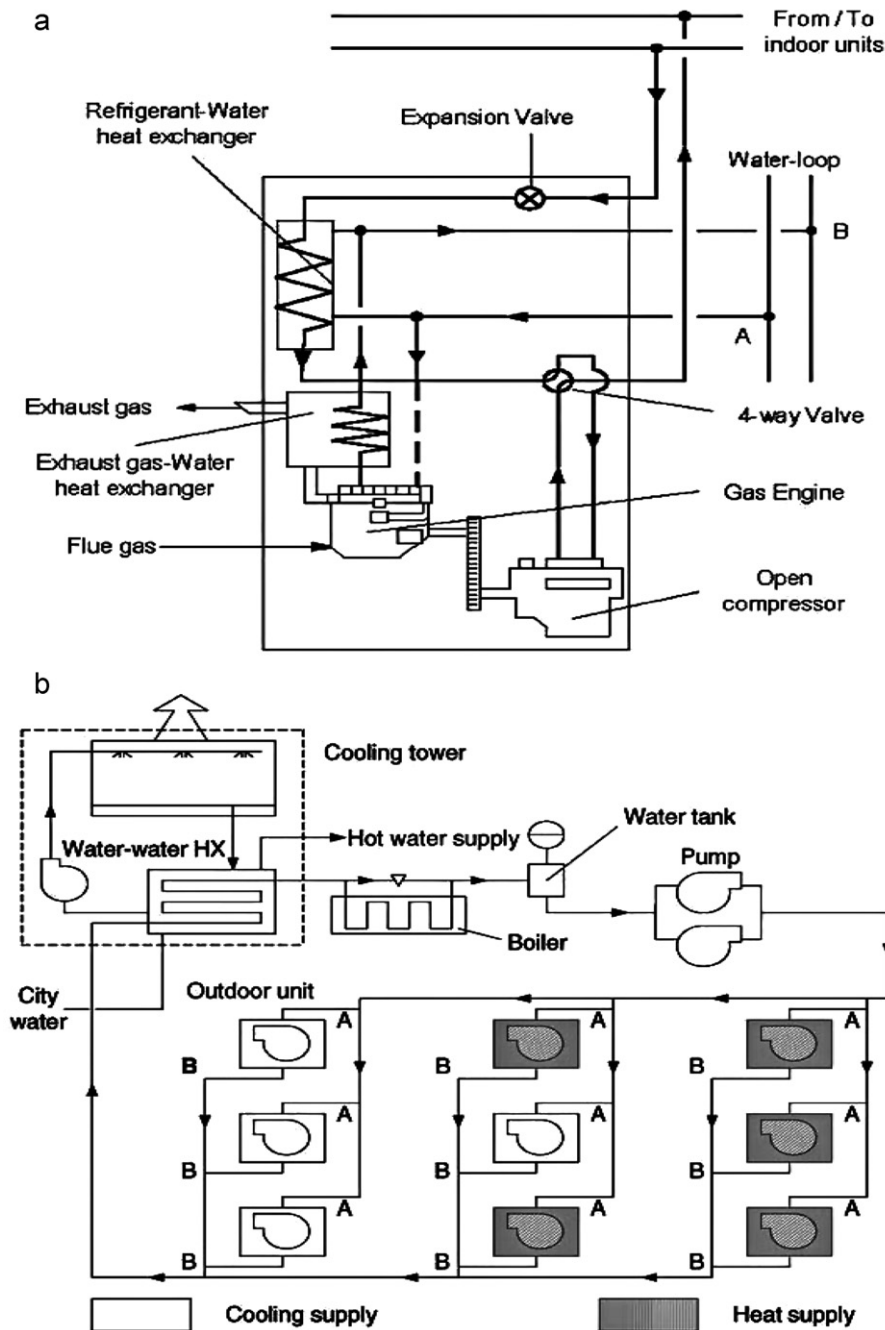


Fig. 6. (a) Schematic view of the outdoor unit of a water-cooled GEHP package, operating in heating mode; (b) schematic view of WLHPS, where the GEHP packages can be applied, among them connecting points are A and B, respectively. Figure is drawn by Lian et al. [10].

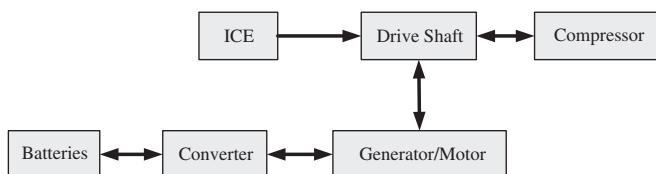


Fig. 7. Block diagram showing the parallel architecture of HPGHP [38].

with other HP systems. Unfortunately heat recovery effect does not influence much while comparing the systems according to their COP values. Recent studies have been

conducted on PER values of GEHP systems. Main studies focused on comparing them with other HP systems according to PER values were done by Li et al. [49] and Yang et al. [32]. Li et al. [49] compared six different air-conditioning systems under three different conditions. They concluded that GEHP systems had the highest PER values. Yang et al. [32] also compared five different heating systems and obtained similar results.

Because of the superiority of PER value in comparing GEHP systems with other HP systems, optimization studies have been generally made by using PER values.

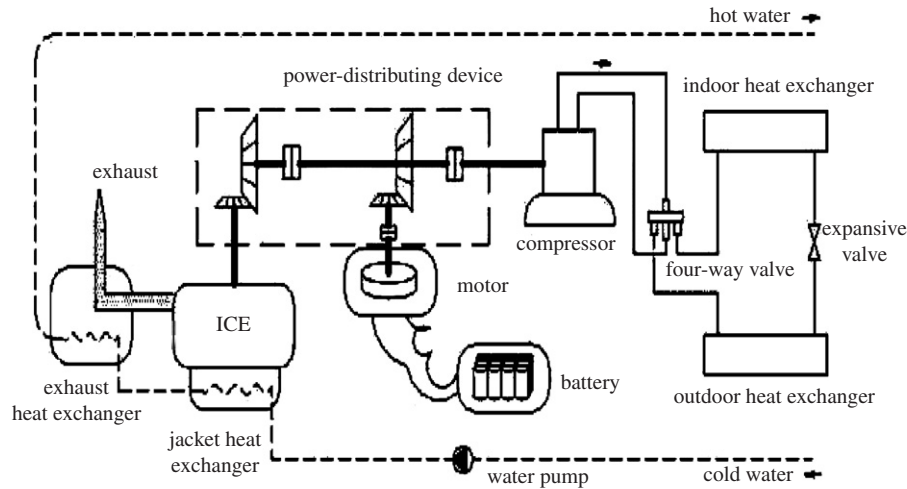


Fig. 8. The structure of the parallel HPGHP system drawn by Ying-Lin et al. [38].

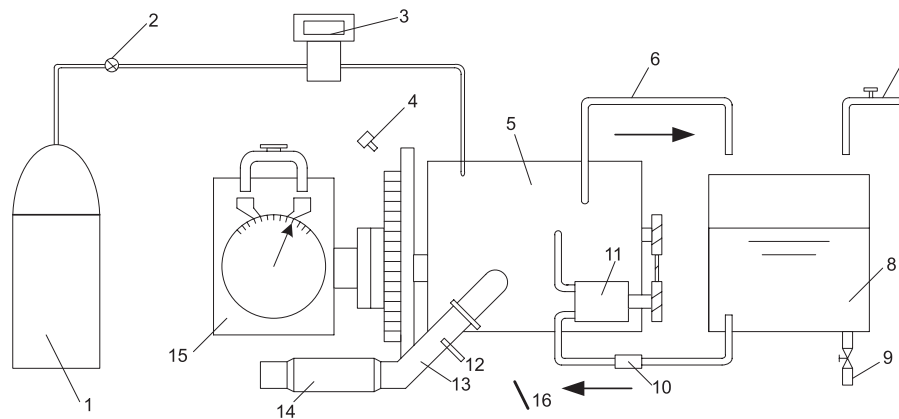


Fig. 9. Diagram of engine waste heat experiment drawn by Zhang et al. [13]: (1) natural gas storage, (2) pressure relief valve, (3) natural gas flow rate meter, (4) tacho-generator, (5) engine, (6) hot water pipe, (7) supplemental water, (8) water tank, (9) draw-off valve, (10) water flow meter, (11) water pump, (12) λ sensor, (13) exhaust pipe, (14) silencer, (15) hydrodynamometer, (16) thermometer.

Li et al. [50] and Zhang et al. [13] reported that PER values increased by decreasing engine speed. It was proved that GEHP systems were more energy saving in the low speed mode and at lower ambient temperatures. In addition, Zhao et al. [52] studied on two combined absorption/compression refrigeration cycles using ammonia and water as the working fluid. They optimized the system according to PER values, and proved that the combined cycle with two solution circuits was the best.

Recently, some studies on exergy efficiency of GEHP systems have also been conducted. Xie et al. [53] worked with a R-134a GEHP at 50°C condenser temperature and at 2°C evaporator temperature. The PER value of this GEHP was calculated to be 1.76, with an exergy efficiency of 0.291 and an energy grade balance efficiency of 0.394.

A research project on a GEHP has been recently implemented by the authors [54]. In this regard, they designed a gas engine driven solar assisted band conveyor HP drying system, as shown in Fig. 12 and applied this system to food drying. The system consists of mainly four sections, namely: (i) a GEHP unit with heating capacity of

18 kW, (ii) a HP unit with scroll modified for compression with enhanced vapour injection, (iii) an air solar collector and (iiii) a band conveyor dryer. The project has been financially supported by The Scientific and Technological Research Council of Turkey (TUBITAK). Within the framework of the project, it is aimed at comparing the new drying system applied for tunnel drying of parsley, broccoli and plums with conventional drying systems (i.e., tray dryer and fluidized bed dryer) based on energy and exergy efficiencies, product quality and economics. This project will help in becoming widespread industrial applications of GEHP systems in drying processes, especially in food industry.

5. Modeling and an illustrative example

In the performance evaluation of GEHP, energy and exergy analysis methods are used. In this regard, the GEHP system may be modeled using the following relations, which are related to HP unit and the whole GHP system [55–65].

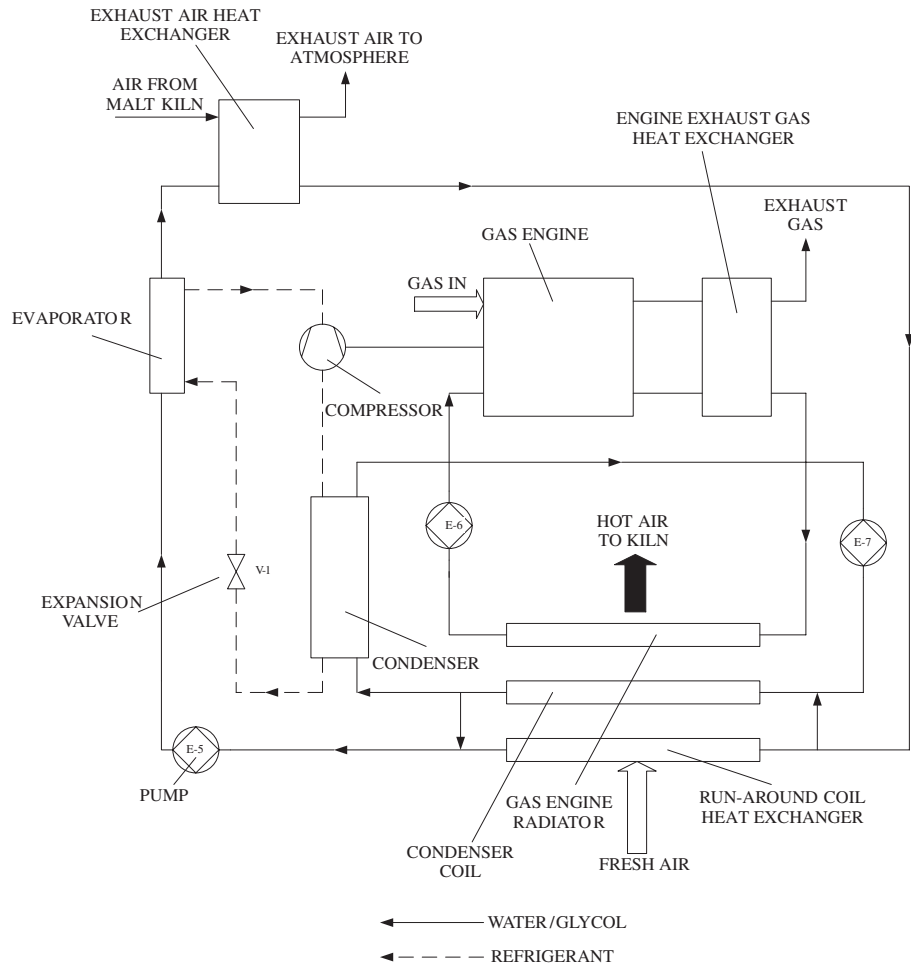


Fig. 10. Schematic of the coupled heat-pump-gas engine system [43].

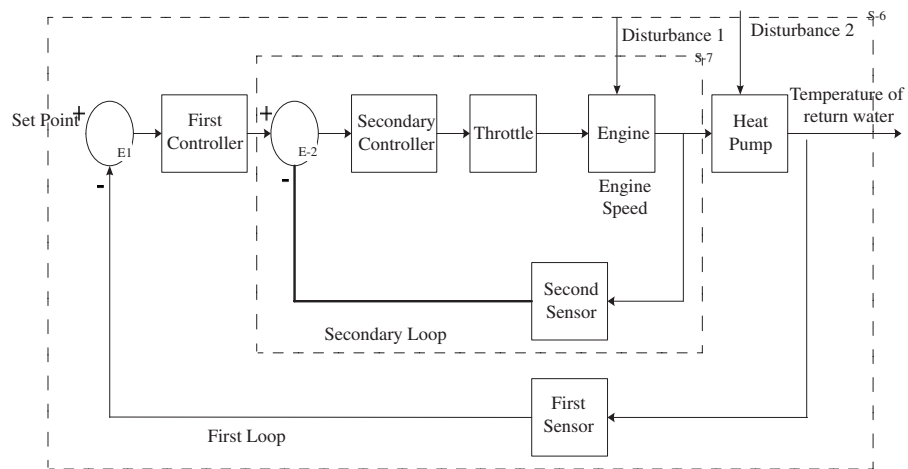


Fig. 11. Schematic diagram of cascade control system [11].

5.1. Modeling

5.1.1. General energy and exergy balance equations

General mass, energy, entropy and exergy balance equations are given in more detail elsewhere [55].

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}, \tag{1}$$

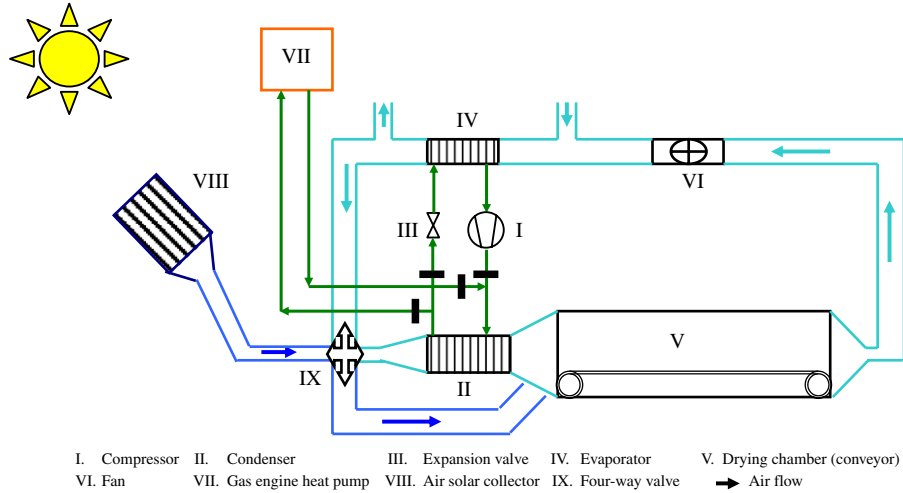


Fig. 12. Schematic view of a gas engine driven solar assisted band conveyor heat pump drying system [54].

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet.

The general energy balance can be written as

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \text{ or } \dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out}, \quad (2)$$

where $\dot{m}$ is the mass flow rate and the subscript in stands for inlet and out for outlet, $\dot{E}_{in}$ is the rate of net energy transfer in, $\dot{E}_{out}$ is the rate of net energy transfer out by heat, work and mass, $\dot{Q} = \dot{Q}_{net,in} = \dot{Q}_{in} - \dot{Q}_{out}$ is the rate of net heat input, $\dot{W} = \dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in}$ is the rate of net work output, and h is the enthalpy per unit mass.

The general exergy balance can be expressed in the rate form as

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \text{ or } \sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in} \psi - \sum \dot{m}_{out} \psi = \dot{E}x_{dest} \quad (3)$$

$$\psi = (h - h_0) - T_0(s - s_0), \quad (4)$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k , $\dot{W}$ is the work rate, ψ is the flow (or specific) exergy, s is the specific entropy and the subscript zero indicates properties at the dead state of P_0 and T_0 ,

The exergy destroyed or the irreversibility may be expressed as follows

$$\dot{I} = \dot{E}x_{dest} = T_0 \dot{S}_{gen}, \quad (5)$$

where $\dot{S}_{gen}$ is the rate of entropy.

Van Gool's exergetic improvement potential in the rate form, denoted $I\dot{P}$, is given by [56,57]

$$I\dot{P} = (1 - \eta)(\dot{E}x_{in} - \dot{E}x_{out}). \quad (6)$$

5.1.2. General energy and exergy efficiency relations

The energy-based efficiency measure of electrical HP unit (COP_{HP}) is calculated as follows [58]:

$$COP_{HP} = \frac{\dot{Q}_{cond}}{\dot{W}_{comp,elec}}. \quad (7)$$

The COP for the GEHP is calculated from [59,60]

$$COP_{GEHP} = \eta_{motor,eff} COP_{HP} + a_{motor,u} \quad (8)$$

or

$$COP_{GEHP} = \eta_{mech} COP_{HP} + (\eta_{total} - \eta_{mech}), \quad (9)$$

where $\eta_{motor,eff}$ is the effective (mechanical) efficiency of the gas engine, $a_{motor,u}$ is the share of gas engine useful waste heat in the primary energy utilization, η_{mech} is the mechanical efficiency of the gas engine, and $\eta_{motor,eff}$ is the total efficiency of the gas engine.

The exergetic coefficient of performance of electrical HP unit is calculated by

$$COP_{ex,HP} = \frac{\dot{Q}_{cond}(1 - \frac{T_0}{T_{cond}})}{\dot{W}_{comp,elec}}. \quad (10)$$

The exergy efficiencies of the electrical HP and GEHP are obtained, respectively, from

$$\varepsilon_{HP} = \frac{\dot{E}x_{heat}}{\dot{W}_{comp,elec}} = \frac{\dot{E}x_{in,condenser} - \dot{E}x_{out,condenser}}{\dot{W}_{comp,elec}}, \quad (11)$$

$$\varepsilon_{\text{GEHP}} = \frac{\dot{E}x_{\text{in,condenser}} - \dot{E}x_{\text{out,condenser}}}{\dot{E}x_{\text{fuel}}}. \quad (12)$$

5.2. An illustrative example

5.2.1. Description of the system

The general relations given in the previous section are applied to an air/water GEHP shown in Fig. 4 [14], which is described by Lazzarin and Noro [14] as follows: “S. Nicola” HVAC plant in Vicenza, Italy features innovative and significant energy savings characteristics. The nominal cooling power is 275 kW (22 Nm³/h of natural gas is the nominal fuel consumption), while in heating mode the output power is 380 kW (19 Nm³/h fuel consumption). These performances are labeled for summer external air 35°C and evaporator input/output 12/7°C; winter external air 10°C and condenser input/output 40/45°C. Heat recovery is taken from the lubricating oil, engine cooling water and partly from the exhaust. The nominal power thus recovered is 109 kW in heating mode and 127 kW in cooling mode, to produce hot water at about 70°C. The energy balance of the system is reported as relative units (primary energy input = 100) and in absolute values (kW) for heating mode. Two hydraulic circuits are provided. The primary one supplies chilled water in summer (7/12°C) and warm water in winter (45/40°C) produced by HP and the secondary one hot water at 70°C given by the heat recovery. The control system is governed by a micro-processor that commands the engine speed regulator and the compressor cylinders chocking.

5.2.2. Energetic and exergetic assessment of gas engine

The energetic and exergetic evaluation of the gas engine has been given in more detail elsewhere [61], while its exergy efficiency may be calculated using the following relation:

$$\varepsilon_{\text{engine}} = \frac{\dot{W}_{\text{eff}}}{\dot{E}x_{\text{fuel}}}, \quad (13)$$

where $\dot{E}x_{\text{fuel}}$ is the exergy of the fuel, which may be found using the relations given in Ref. [62].

5.2.3. Energetic and exergetic assessment of GEHP components

The GEHP consists of a HP unit (compressor, condenser, evaporator and expansion valve), a gas engine and heat exchangers (i.e., exhaust recovery and engine cooling recovery), as shown in Fig. 4. The energy and exergy balance (exergy destruction) relations for the components of a ground-source HP system have been derived for the author elsewhere [63,64], while they are obtained along with their exergy efficiencies for an air/water GEHP shown in this figure as follows:

Compressor (I):

$$\dot{m}_1 = \dot{m}_{2,s} = \dot{m}_{\text{act},s} = \dot{m}_r, \quad (14a)$$

$$\dot{W}_{\text{comp}} = \dot{m}_r(h_{2,\text{act}} - h_1) \quad (14b)$$

$$\dot{E}x_{\text{dest,comp}} = \dot{m}_r(\psi_1 - \psi_{2,\text{act}}) + \dot{W}_{\text{comp,elec}}, \quad (14c)$$

$$\varepsilon_{\text{comp}} = \frac{\dot{E}x_{2,\text{act}} - \dot{E}x_1}{\dot{W}_{\text{comp,elec}}}, \quad (14d)$$

where heat interactions with the environment are neglected.

Condenser (II):

$$\dot{m}_2 = \dot{m}_3 = \dot{m}_r, \quad (15a)$$

$$\dot{m}_7 = \dot{m}_8 = \dot{m}_w, \quad (15b)$$

$$\dot{Q}_{\text{cond}} = \dot{m}_r(h_{2,\text{act}} - h_3), \quad (15c)$$

$$\dot{Q}_{\text{cond}} = \dot{m}_w C_{p,w}(T_8 - T_7), \quad (15d)$$

$$\dot{E}x_{\text{dest,cond}} = \dot{m}_r(\psi_{2,\text{act}} - \psi_3) + \dot{m}_{w,\text{th}}(\psi_7 - \psi_8), \quad (15e)$$

$$\varepsilon_{\text{cond}} = \frac{\dot{E}x_8 - \dot{E}x_7}{\dot{E}x_{2,\text{act}} - \dot{E}x_3} = \frac{\dot{m}_w(\psi_8 - \psi_7)}{\dot{m}_r(\psi_{2,\text{act}} - \psi_3)} \quad (15f)$$

Expansion (throttling) valve (III):

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_r, \quad (16a)$$

$$h_3 = h_4, \quad (16b)$$

$$\dot{E}x_{\text{dest,exp}} = \dot{m}_r(\psi_3 - \psi_4), \quad (16c)$$

$$\varepsilon_{\text{exp}} = \frac{\dot{E}x_4}{\dot{E}x_3} = \frac{\psi_4}{\psi_3}. \quad (16d)$$

Evaporator (IV):

$$\dot{m}_4 = \dot{m}_1 = \dot{m}_r, \quad (17a)$$

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_{\text{air}}, \quad (17b)$$

$$\dot{Q}_{\text{evap}} = \dot{m}_r(h_1 - h_4), \quad (17c)$$

$$\dot{Q}_{\text{evap}} = \dot{m}_{\text{air}} C_{\text{air,p}}(T_6 - T_5), \quad (17d)$$

$$\dot{E}x_{\text{dest,evap}} = \dot{m}_r(\psi_4 - \psi_1) + \dot{m}_{\text{air}}(\psi_6 - \psi_5), \quad (17e)$$

$$\varepsilon_{\text{evap}} = \frac{\dot{E}x_6 - \dot{E}x_5}{\dot{E}x_4 - \dot{E}x_1} = \frac{\dot{m}_{w,\text{prt}9}(\psi_6 - \psi_5)}{\dot{m}_r(\psi_4 - \psi_1)}. \quad (17f)$$

Heat exchanger for engine cooling water recovery (V):

$$\dot{m}_9 = \dot{m}_{10} = \dot{m}_{\text{recovery,w}}, \quad (18a)$$

$$\dot{m}_{15} = \dot{m}_{16} = \dot{m}_{\text{cooling,w}}, \quad (18b)$$

$$\dot{Q}_{\text{cooling,w}} = \dot{m}_{\text{cooling,w}}(h_{15} - h_{16}), \quad (18c)$$

$$\dot{Q}_{\text{recovery,w,I}} = \dot{m}_{\text{recovery,w}} C_{\text{recovery,w,p}}(T_{10} - T_9) \quad (18d)$$

$$\begin{aligned} \dot{E}x_{\text{dest,engine cooling}} &= \dot{m}_{\text{cooling,w}}(\psi_{15} - \psi_{16}) \\ &\quad + \dot{m}_{\text{recovery,w}}(\psi_9 - \psi_{10}), \end{aligned} \quad (18e)$$

$$\varepsilon_{\text{HE,cooling,w}} = \frac{E\dot{x}_{10} - E\dot{x}_9}{E\dot{x}_{15} - E\dot{x}_{16}} = \frac{\dot{m}_{\text{recovery,w}}(\psi_{10} - \psi_9)}{\dot{m}_{\text{cooling,w}}(\psi_{15} - \psi_{16})}. \quad (18f)$$

Heat exchanger for exhaust recovery (VI):

$$\dot{m}_{10} = \dot{m}_{11} = \dot{m}_{\text{recovery,w}}, \quad (19a)$$

$$\dot{m}_{12} = \dot{m}_{13} = \dot{m}_{\text{exhaust,gas}}, \quad (19b)$$

$$\dot{Q}_{\text{exhaust,gas}} = \dot{m}_{\text{exhaust,gas}}(h_{12} - h_{13}), \quad (19c)$$

$$\dot{Q}_{\text{recovery,w,II}} = \dot{m}_{\text{recovery,w}} C_{\text{recovery,w,p}}(T_{11} - T_{10}), \quad (19d)$$

$$\begin{aligned} E\dot{x}_{\text{dest,engine exhaust}} &= \dot{m}_{\text{exhaust gas}}(\psi_{12} - \psi_{13}) \\ &+ \dot{m}_{\text{recovery,w}}(\psi_{10} - \psi_{11}), \end{aligned} \quad (19e)$$

$$\varepsilon_{\text{HE,exhaust gas}} = \frac{E\dot{x}_{11} - E\dot{x}_{10}}{E\dot{x}_{12} - E\dot{x}_{13}} = \frac{\dot{m}_{\text{recovery,w}}(\psi_{11} - \psi_{10})}{\dot{m}_{\text{exhaust gas}}(\psi_{12} - \psi_{13})}. \quad (19f)$$

Circulating pump (VII):

$$\dot{m}_{14} = \dot{m}_{15s} = \dot{m}_{15,\text{act}} = \dot{m}_{\text{cooling,w}} \quad (20a)$$

$$\dot{W}_{\text{pump}} = \dot{m}_{\text{cooling,w}}(h_{15,\text{act}} - h_{14}), \quad (20b)$$

$$E\dot{x}_{\text{dest,pump}} = \dot{m}_{\text{cooling,w}}(\psi_{14} - \psi_{15}) + \dot{W}_{\text{pump,elec}}, \quad (20c)$$

$$\dot{W}_{\text{pump,elec}} = \dot{W}_{\text{pump}}/(\eta_{\text{pump,elec}}\eta_{\text{pump,mech}}), \quad (20d)$$

$$\varepsilon_{\text{pump}} = \frac{E\dot{x}_{15} - E\dot{x}_{14}}{\dot{W}_{\text{pump,elec}}} = \frac{\dot{m}_{\text{cooling,w}}(\psi_{15} - \psi_{14})}{\dot{W}_{\text{pump,elec}}}. \quad (20e)$$

Relative irreversibility is given by:

$$\text{RI} = \frac{E\dot{x}_i}{E\dot{x}_{\text{total}}}. \quad (21)$$

5.2.4. Results and discussion

The system considered could not be evaluated using numeric values in terms of energetic and exergetic aspects since they were not available in Ref. [14]. However, the following assessments may be done: Since compressor power depends strongly on the inlet and outlet pressures, any heat exchanger improvements that reduce the temperature difference will reduce compressor power by bringing the condensing and evaporating temperatures closer together. From a design standpoint, compressor irreversibility can be reduced independently. Recent advances in the market have led to the use of scroll compressors. Irreversibilities in heat exchangers (i.e., evaporator, condenser and heat recovery components) occur due to the temperature differences between the two heat exchanger fluids, pressure losses, flow imbalances and heat transfer with the environment. The irreversibility associated with the expansion valve (capillary tube) due to the pressure drop of the refrigerant passing through it. The only way to eliminate the throttling loss is to replace the capillary tube with an isentropic turbine (an isentropic

expander) and to recover some shaft work from the pressure drop.

6. Conclusions

For development of sustainable energy, three important technological changes are required: energy economies on the demand side, efficiency improvements in the energy production, and renewing of fossil fuels by various sources of renewable energy. This study reviewed GEHP systems for residential and industrial applications. Energy and exergy balance equations were also derived for an illustrative example.

The main conclusions, which may be drawn from the results of the present study, are listed below:

- Heat gained by heat recovery can be provided approximately by 30% of the total heating capacity for GEHP systems.
- System energy efficiency can be maximized with low engine speed mode.
- When ambient temperature is low, energy saving made by GEHP systems increases.
- Although there are many studies performed on energy analysis of GEHPs, exergy analyses are very few in numbers.
- GEHP systems become more efficient when used both in water and space heating.
- Generally, studies concentrated on air-conditioning and water heating processes. There are very few studies focused on industrial applications of GEHP systems, although GEHP systems can be suitable for especially drying processes.
- GEHP systems can become more efficient with improvement of appropriate control systems and equipments.

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